Pressure to perform: Is cardiac output estimation from arterial waveforms good enough for routine use?*

Improving organ perfusion by managing pressure and flow within the circulation is central to judging the effects of fluid and vasoactive drug administration in critically ill patients. For this reason, blood pressure is measured routinely and usually invasively, via a radial artery catheter, in patients in the intensive care unit. Because invasive blood pressure provides a continuous signal that allows the effect of interventions to be seen immediately, it follows that there is interest in having cardiac output constantly accessible as well. There are several technical options for measuring cardiac output continuously during routine clinical care: most result from the development of the pulmonary artery catheter, use of esophageal Doppler, or devices that derive stroke volume and cardiac output from the arterial pressure waveform—the pressure pulse methods. From a commercial perspective, pressure pulse methods can be divided into those that rely on being "calibrated" based on an independent bolus cardiac output measurement (PiCCO System, Pulsion Medical Systems, Munich, Germany and LiDCO Plus, LiDCO Ltd, Cambridge, UK) and those that are "uncalibrated" (Vigileo FloTrac, Edwards Lifesciences, CA and MostCare PRAM, Vytech SRL, Venice, Italy).

Using arterial waveform analysis to generate beat-to-beat cardiac output is an attractive concept, and indeed, this general approach is now marketed under its own branding—so-called "minimally invasive hemodynamic monitoring." The devices that are still more popular in Europe than in the United States, are relatively easy to use, and present their information clearly, often with displays that are designed to guide therapy in particular directions. Yet, the concepts behind the different methods for deriving cardiac output from a peripheral blood pressure wave are complex, and the differences in the methodologies are highly technical. Furthermore, the exact algorithms used are commercial secrets not in the public domain, although they are said to use variations of classic physiologic and analytical approaches that have been described in the literature. For institutions and clinicians thinking of investing in and using these methodologies, it is therefore timely to consider just how reliably stroke volume and cardiac output can be derived from the arterial pressure signal.

In this issue of *Critical Care Medicine*, Sun et al (1) have addressed the issue with an article entitled "The cardiac output from blood pressure clinical algorithm trial." The investigators used their computerized Multi Parameter Intelligent Monitoring of Intensive Care II database to evaluate eight different algorithms to estimate cardiac output from data collected on 120 patients during "routine clinical operations" at Beth Israel Deaconess Medical Center in Boston. Strengths of their approach are as follows:

- Collecting a large database of important physiologic data and using it for multiple purposes (1, 2);
- Evaluating the collected data, using eight different pressure pulse algorithms to estimate cardiac output;
- Providing the database in a publicly and freely available format so that other investigators and commercial vendors have free access to it;
- Stimulating and challenging investigators interested in this important area of patient assessment to improve estimates of cardiac output from arterial blood pressure signals.

Although the authors have provided a "stepping stone" for progression in the field of near-continuous cardiac output measurement, there are several issues and challenges that have not been resolved, which are listed as follows:

- The quality of the recorded physiologic signals of blood pressure and cardiac output measures must be optimal. Collecting data from routine clinical operations may result in problems, as evidenced by the quality of the blood pressure signals shown in Figure 1 and the derived data shown in Figure 4. Dynamic response of the pressure signals was poor, and the "zeroing" status of the pressure transducer was unknown (3, 4). In addition, only a single thermodilution cardiac output was performed (5).
- It is important to test commercial devices that estimate cardiac output using the arterial pressure waveform. Some have reported that their devices are more accurate than the algorithms tested here (6). The authors stated that the commercial algorithms were "proprietary" and thus not available for them to test. Their statement was surprising because the authors had the "blood pressure signals" available and could have converted them into analog signals and "injected" them into the commercial devices and thus made the comparisons.
- It is important that investigators come to grips with "how good is good enough" as analyses and projections are made (7, 8). Based on the statistics and scatter plots of Figure 3, huge variations in the errors indicate that the cardiac output and other derived parameter estimates were very noisy.
- The authors chose to use methods that "aggregated all the findings" rather than exploring individual situations, such as when patients were in shock or receiving vasodilators. It was unclear if the patient's medication information was even available to them from their database and from the CareVue computerized charting system (Philips Medical Systems, Andover, MA). If such data had been available, it should have

*See also p. 72.

Key Words: cardiac output; signal quality; pulse contour; thermodilution; comparison of cardiac output methods

Mr. Beale has received research support from Lidco, Ltd. Dr. Gardner has not disclosed any potential conflicts of interest.

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DOI: 10.1097/CCM.0b013e3181935189

been added to the MIMIC II database to help answer these questions.

- Furthermore, the authors did not discuss when and how frequently the pulse pressure cardiac output method needed to be "recalibrated." For example, some commercial device manufacturers recommend recalibration at 8-hr intervals.
- Unfortunately, the authors did not seek to discover the true estimates of cardiac output, but instead merely relied on data coming from routine, but unspecified, data collections protocols at their clinical facility.
- In many situations, the authors seemed to be promoting the MIMIC II database, rather than making the comparisons noted in the title.

The authors raise an unusually rich number of clinical, scientific, and methodologic issues that will be valuable for future discussion. The present study also provides a stimulus to the critical care community to determine whether better data collection and testing methodologies for estimating cardiac output can be achieved from arterial pressure signals. Admittedly, based on the data presented in this article, it would be easy to surmise that available methods were of marginal clinical value at best. Even though the Liljestrand and Zander method from 1928 gave the best estimates, the variation in the cardiac output was still too wide (+1.41 to −1.76 L/min) and gave the correct directional trend for cardiac output for only 78% of the measures. Also, by aggregating the data, Sun et al have not identified particular situations or patient groups where performance might be better or worse, for instance when vasopressors are used, in hypovolemia, in the elderly or when there is a history of hypertension. As a result, situations where the tested methods might be useful or, even more crucially, be likely to mislead and to be harmful have not been clearly identified. Importantly, of course, this criticism is also true of the commercial systems, which have generally only been tested in small, short-term studies in convenient patient groups (e.g., postoperative cardiac surgery) and with the results also presented in aggregate form, usually compared with pulmonary artery catheter-derived thermodilution cardiac output.

Is it fair to assume that these devices are not yet good enough for clinical use? Clinical users of commercial devices that were not tested here presumably believe that those instruments give reliable information and may well outperform the algorithms tested here—a perspective the manufacturers would certainly endorse. However, the commercial devices may use analytical approaches that are sufficiently different from each other that it would be wrong to assume that they are interchangeable in their performance without confirming data. Indeed, there is still a striking paucity of performance data for these devices considering their increased market penetration and the magnitude of the health care dollar investment being made.

By presenting the shortcomings of the published algorithms for deriving cardiac output continuously from the arterial pressure waveforms, Sun et al have challenged manufacturers of commercial devices to demonstrate how well their systems perform using relevant populations in real-life situations and to do so in a fashion that avoids the pitfalls outlined above. Clinicians should independently undertake the challenge to carry out and publish results of experiments to establish the performance capabilities of commercially available devices.

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REFERENCES

1. Sun JX, Reisner AT, Saeed M, et al: The cardiac output from blood pressure algorithm trial. *Crit Care Med* 2009; 37:72–80
2. Aboukhalil A, Nielsen L, Saeed M, et al: Reducing false alarm rates for critical arrhythmias using the arterial blood pressure waveform. *J Biomed Inform* 2008; 41:442–451
3. Gardner RM, Warner HR, Toronto AF, et al: Catheter-flush system for continuous monitoring of central arterial pulse waveform. *J Appl Physiol* 1970; 29:911–913
4. Gardner RM: Direct blood pressure measurement—Dynamic response requirements. *Anesthesiology* 1981; 54:227–236
5. Nilsson LB, Nilson JC, Skovgaard LT, et al: Thermodilution cardiac output—Are three injections enough? *Acta Anaesthesiol Scand* 2004; 48:1322–1327
6. Pearse RM, Ikram K, Barry J: Equipment review: An appraisal of LiDCO plus method of measuring cardiac output. *Crit Care* 2004; 8:190–195
7. Gardner RM: Editorial: Continuous cardiac output: How accurate and how timely? [editorial]. *Crit Care Med* 1998; 26:1302–1303
8. Beale R: Editorial: Echoes of the past? *Crit Care Med* 2008; 36:1950–1951